

**Shape Shifting Satellites
in
Binary Near-Earth Asteroids:
Do Meteoroid Impacts
Play a Role in
BYORP Orbital Evolution?**

By

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Abstract

Less than catastrophic meteoroid impacts over 10^5 years may change the shape of small rubble-pile satellites in binary NEAs, lengthening the average BYORP (binary Yarkovsky-Radzievskii-Paddack) rate of orbital evolution. An estimate of shape-shifting meteoroid fluxes give numbers close enough to causing random walks in the semimajor axis of binary systems to warrant further investigation.

1. Introduction

Perhaps $\sim 15\%$ of the near-Earth asteroids (NEAs) are binaries (**Pravec *et al.*, 2006**). The dynamical lifetimes of these small binaries is thought to be $\sim 10^5$ yr due to the binary Yarkovsky-O'Keefe-Radzievskii Paddack (BYORP) effect (**Cuk and Burns, 2005**). BYORP either increases the system's semimajor axis to the point where the satellite escapes, or decreases it until the satellite reaches the primary. The large percentage of binaries may mean that binaries are created at a high rate, destroyed at a slow rate, or the dynamical lifetimes are longer than $\sim 10^5$ yr, or some combination of these.

One reason for believing the dynamical lifetimes are longer is that the 10^5 years refers to uninterrupted BYORP evolution. If occasionally a synchronous satellite were to have an episode where the satellite flipped and the other end thereafter synchronously pointed at the primary, then the BYORP effect would change sign and the evolution would be reversed until the next flip, lengthening the dynamical lifetime via a random walk. There purely dynamical reasons why such end-for-end switching might occur (**Cuk and Nesvorný, 2010**). Also, a satellite may accrete mass from the primary; 1999 KW4 might speed up from the YORP effect, for example (**Ostro *et al.*, 1996**), and throw off pieces which end up on the satellite, changing its shape and altering BYORP.

We examine here another possible mechanism as to why steady BYORP evolution might be interrupted: less than catastrophic meteoroid collisions with the satellite of an NEA. The idea is this: most asteroids appear to be rubble-piles (**e.g., Harris *et al.*, 2009**). BYORP depends on the satellite's shape. If the satellite is a rubble-pile, then a collision may disturb the rubble structure enough to change the shape of the satellite, altering the BYORP effect, including perhaps changing its sign. If the collisions happen often enough, then once again a sort of random walk will ensue, lengthening the average dynamical lifetime. The amount of energy needed for an impactor to significantly modify the shape of small rubble-pile satellites is estimated below, along with the frequency of such hits. Changes in satellite spin state are ignored. Detailed modeling of the impact process is beyond the scope of this paper.

2. Gravitational potential energy

We forsake detailed computations of shape changes here for a simple estimate based on the energy required to pull apart a spherical rubble-pile held together only by gravity; i.e., a self-gravitating sphere composed of millions of frictionless, non-sticky marbles. The gravitational potential energy U of a sphere of radius R and uniform density ρ is

$$U = -\frac{3GM^2}{5R} = -\frac{3G}{5R} \left(\frac{4\pi}{3} \rho R^3 \right)^2 = -\frac{48}{45} G \pi^2 \rho^2 R^5 \quad (1)$$

where G is the universal constant of gravitation (e.g., **Rubincam, 1979**). This is the energy required to pull apart all the marbles composing the sphere and send them to infinity, where they arrive with zero velocity. Let

$$\Delta U = |U|F \quad (2)$$

where ΔU is the change in energy necessary to significantly alter the BYORP effect, such as cancel, double, or reverse the sign of the effect.; thus ΔU is expressed as a fraction F of U in the above equation.

The value for F is estimated via an energy argument. Consider a non-rotating spherical satellite of mass M and radius R as above. Suppose an impact is energetic enough to fission the satellite into a contact binary consisting of two non-rotating spherical asteroids as shown in Fig. 1. Neither the assumed original spherical satellite nor the resulting contact binary will actually exhibit BYORP; they are too symmetrical. The purpose of the estimate is to make an educated guess based on easily computed shapes, without actually constructing an explicit model.

In the contact binary, assume the larger object has mass M_1 and radius R_1 , and the smaller has mass M_2 and radius $R_2 = fR$. Being a contact binary, M_2 simply rests on M_1 's

surface. Also, both M_1 and M_2 have the same uniform density ρ as M . Moreover, assume the total mass and volume are conserved. In this case $R^3 = R_1^3 + R_2^3$, so that $R_1 = (1 - f^3)^{1/3}R$, $M_2 = f^3M$, and $M_1 = (1 - f^3)M$. The gravitational potential energy is now

$$U' = -\frac{3}{5} \frac{GM_1^2}{R_1} - \frac{3}{5} \frac{GM_2^2}{R_2} - \frac{GM_1M_2}{R_1 + R_2} \quad (3)$$

where the last term is the interaction energy of the two objects. The factor F as a function of f is then

$$F = \left| \frac{U' - U}{U} \right| = 1 - (1 - f^3)^{5/3} - f^5 - \frac{5f^3(1 - f^3)}{3[f + (1 - f^3)^{1/3}]} \quad (4)$$

and is shown in Fig. 2. An educated guess is that $f \approx 0.315$, so that $F = 0.01$; thus the gravitational potential energy changes by 1% for this value of f .

3. Impactor mass and velocity

When an impactor hits the satellite, it is the explosion that provides the energy for the shape change. It is necessary to estimate the impactor's mass in order to compute the flux of impactors, because the flux depends on mass. The impactor's kinetic energy is $mv^2/2$, where m is its mass, and v is its velocity. Let $0 \leq \xi \leq 1$ be the efficiency with which the impactor's kinetic energy is transformed into the required potential energy ΔU . In this case

$$\frac{\xi}{2} mv^2 = |U|F = \frac{3GM^2}{5R} F \quad (5)$$

Solving for m yields

$$m = \frac{6GM^2}{5Rv^2} \left(\frac{F}{\xi} \right) = \frac{6G}{5Rv^2} \left(\frac{4\pi}{3} \rho R^3 \right)^2 \left(\frac{F}{\xi} \right) = \frac{96\pi^2 G \rho^2}{45v^2} R^5 \left(\frac{F}{\xi} \right), \quad (6)$$

so that the lower the efficiency ξ , the greater the impactor mass needed to effect shape changes.

Throughout the following it will be assumed that the satellite has $\rho = 2000 \text{ kg m}^{-3}$. The low density ρ is due to the voids in the rubble-pile.

To get an idea of the magnitude of m in (6), it is necessary to estimate v , F , and ξ . Velocity v is the least uncertain of these. **Suggs et al. (2010)** find that objects in the 0.1 - 10 kg range impacting the Moon overwhelmingly come from meteoroid streams in comet-like orbits. It will be assumed here that impactors slightly smaller than 0.1 kg also follow these orbits. The Taurids have relatively low velocities of $\sim 2.4 \times 10^4 \text{ m s}^{-1}$, while the Leonids have extremely high velocities of $\sim 7.1 \times 10^4 \text{ m s}^{-1}$ (e.g., **Moser et al., 2011, Table 3; Kokhirova and Borovicka, 2011**). The Geminids have intermediate velocities of $\sim 3.5 \times 10^4 \text{ m s}^{-1}$ (e.g., **Moser et al., 2011**). A Geminid-like value of $v = 3.333 \times 10^4 \text{ m s}^{-1}$ is adopted here for v (so that conveniently $v^2 = 10^9 \text{ m}^2 \text{ s}^{-2}$).

Of the list of 37 near-Earth binaries compiled by W. R. Johnston, many have satellites with $R \approx 150 \text{ m}$, while the largest on the list, 2001 SN₂₆₃, has $R \approx 500 \text{ m}$ (<http://www.johnstonsarchive.net/astro/asteroidmoons.html>). For a satellite with $R = 100 \text{ m}$, $M = 8.4 \times 10^9 \text{ kg}$, $V_{esc} = (2GM/R)^{1/2} = 0.11 \text{ m s}^{-1}$, $g = GM/R^2 = 5.6 \times 10^{-5} \text{ m s}^{-2}$, and $U = -(3/5) GM^2/R = -2.8 \times 10^7 \text{ J}$, where V_{esc} is the escape velocity and g is the surface acceleration of gravity. For such a 100 m satellite,

$$m = 0.056 (F/\xi) \text{ kg} \quad (7)$$

by (6). For the likely values of $F < 0.1$ and $\xi > 0.001$, impactor masses fall in or a little below the range studied by **Suggs et al. (2010)**; so choosing v as a meteoroid stream velocity seems self-consistent and reasonable.

The factor F has already been estimated to be ~ 0.01 . It remains to guess ξ . Kinetic energy may be lost through the escape of ejecta. An impact on a satellite made up of only

regolith would be able to scatter loose material, but the medium is highly dissipative. An impact on a rubble-pile composed of boulders would expend much energy in breaking the chemical bonds holding the rock together, but the seismic shaking might jostle the rubble-pile enough into changing shape (e.g., **Sanchez and Scheeres, 2009**). If the process is only 1% efficient regardless of composition, then $\xi = 0.01$, which gives $F/\xi = 1$. Plugging this in (7) gives for the 100 meter satellite $m = 0.056$ kg, which is a mere two English ounces (2 oz.).

From these considerations it seems sensible to assume that F/ξ may be somewhere between the limits of $0.1 \leq F/\xi \leq 10$. This range is explored below.

4. Impact flux

The impact rate on the satellite will be found next. For the Earth a good approximation is (e.g., **Bland, 2005**)

$$N_E(> m) = B_E m^{-\alpha} \quad (8)$$

where $N_E(> m)$ is the number of meteoroids per year which enter the Earth's atmosphere with mass $> m$, and B_E and α are constants. The above equation can be written

$$\log N_E(> m) = -\alpha \log m + \log B_E \quad (9)$$

where the logarithm is base 10. For meteoroids with masses in the range $1 \text{ kg} < m < 10 \text{ kg}$

$$\log N_{E,1} = -0.926 \log m + 4.739, \quad (10)$$

(**Bland, 2005; Bland and Artemieva, 2006**), so that in this case $\alpha = 0.926$ and $\log B_E = 4.739$. (See also **Silber et al. (2009)** for similar parameters.)

Curiously, there appears to be a break in the curve at smaller masses. **Bland (2005)** and **Bland and Artemieva (2006)** find that

$$\log N_{E,2}(>m) = -0.480 \log m + 4.568 \quad (11)$$

for $m < 1$ kg, based on the fireball data of **Halliday *et al.* (1989)**. According to (11), meteoroids are less numerous than would be expected by extending (10) to masses < 1 kg.

The lunar impacts tend to support (11) more than they do (10). **Suggs *et al.* (2011)** find that N_E is $\sim 150,000 \text{ yr}^{-1}$ (their Fig. 6), based on the lunar data for $m > \sim 0.1$ kg and with no account being taken of the greater focusing factor of the Earth relative to the Moon (R. M. Suggs, private communication, 2012). Assuming a focusing factor of 1.11 for the Earth (see below) and ignoring that of the Moon, their figure rises to $\sim 165,000 \text{ yr}^{-1}$, which is 50% higher than (11), but still closer to the $N_E = 111,686 \text{ yr}^{-1}$ given by (11) than the $N_E = 462,381 \text{ yr}^{-1}$ given by (10). The lunar data thus give some support for the downturn in flux for masses less than 1 kg. However, it should be noted that the lunar lower limit of 0.1 kg is approximate, and the value of N_E based on lunar data may go up or down depending on how accurately the lower limit of 0.1 kg can be established.

Assume that the binary system is an NEA and an orbit about the Sun which is orbit similar to that of the Earth; then the impact rate $N_i(>m)$ on the satellite will be approximately

$$N_i(>m) = 4\pi R^2 N_{E,i}(>m) / (\sigma_{\text{Opik}} A_E) , \quad (12)$$

which can be written

$$N_i(>m) = \frac{4\pi B_E}{\sigma_{\text{Opik}} A_E} \left(\frac{45}{96\pi^2 G \rho^2} \right)^\alpha R^{2-5\alpha} \left(\frac{\xi v^2}{F} \right)^\alpha \text{yr}^{-1} \quad (13)$$

using (6), where $i = 1$ if the impactors follow (10) and $i = 2$ if they follow (11). Also, $A_E = 5.1 \times 10^{14} \text{ m}^2$ is the area of the Earth, $4\pi R^2$ is the area of the satellite, and

$$\sigma_{\text{Öpik}} = 1 + \left(\frac{v_{\text{esc}}}{v} \right)^2 \quad (14)$$

is **Öpik's (1951)** gravitational focusing factor due an object's gravity, which pulls in meteoroids that would otherwise miss it. Here v_{esc} is the Earth's escape velocity, and v the impactor velocity at a great distance from Earth. Substituting $v_{\text{esc}} = 1.1 \times 10^4 \text{ m s}^{-1}$ and $v = 3.3 \times 10^4 \text{ m s}^{-1}$ in the above equation yields $\sigma_{\text{Öpik}} = 1.111$; this value is used here. The focusing factor for the satellite is taken as unity because small asteroids have so little gravitation.

If the break in the curve is somehow incorrect and (10) holds for $m < 1 \text{ kg}$, then $B_E = 54828 \text{ yr}^{-1}$ and $\alpha = 0.926$, so that for the satellite

$$N_1(> m) = 17.5 \times 10^{-5} \left(\frac{100}{R} \right)^{2.63} \left(\frac{\xi}{F} \right)^{0.926} \text{ yr}^{-1} . \quad (15)$$

On the other hand, the data suggest that (11) more nearly holds. In this case $B_E = 36982 \text{ yr}^{-1}$ and $\alpha = 0.480$, so that the number of hits per year on the satellite would be

$$N_2(> m) = 3.3 \times 10^{-5} \left(\frac{100}{R} \right)^{0.4} \left(\frac{\xi}{F} \right)^{0.480} \text{ yr}^{-1} . \quad (16)$$

5. Results

Let

$$H_1 = 10^5 N_1(> m) \quad (17)$$

be the number of hits in 10^5 yr when the meteoroid masses follow N_1 , and

$$H_2 = 10^5 N_2(> m) \quad (18)$$

be the number of hits over the same time interval if the meteoroid masses follow N_2 . H_2 and H_1 are plotted in Figs 3 and 4, respectively, as functions of R , for the values $F/\xi = 0.1, 1$, and 10 .

The mass m required for an impactor to substantially alter the shape of a 100 m rubble-pile found above is surprisingly small. For the assumed value of v and for $F/\xi = 1$, it is only 0.056 kg. However, $F/\xi = 1$ is little more than an educated guess. Can the mass really be as small as the amount of loose change in one's pocket?

Assume $R = 100$ m. If the downturn in flux suggested by the terrestrial fireballs is indeed real, then (16) holds, and $H_2 = \sim 3$ by (18) for $F/\xi = 1$ (see Fig. 3). The shape changes would affect BYORP evolution only a little; there would not enough hits over 10^5 years to give much of a random walk in the semimajor axis of the orbit. However, the high (and perhaps unlikely) value $F/\xi = 10$ would lengthen the dynamical lifetime by maybe something like a factor of $(H_2)^{1/2} = 10^{1/2} = \sim 3.3$, which would be more significant.

On the other hand, if the dearth of small impactors is somehow bogus and (17) gives the real, much higher flux, then the number of hits could be much higher: $H_1 = 17.5$ for $R = 100$ m and $F/\xi = 1$ (see Fig. 4). This would lengthen the average dynamical lifetime by perhaps a factor of $\sim (H_1)^{1/2} = (17.5)^{1/2} = \sim 4$ over uninterrupted BYORP, which would be substantial. The number of hits H_1 can be very high for $F/\xi > 1$, giving a long random walk (Fig. 4).

The lunar impact data are in between H_1 and H_2 . For instance, the flux is 50% greater than that suggested by the fireballs. For $R = 100$ m and $F/\xi = 1$, the number of hits in 10^5 yr is $1.5 \times H_2 = 5$, still rather small for a random walk.

It should be noted from (15) that the flux of shape-changing impactors can depend strongly on satellite radius R if the meteoroids follow N_1 ; the flux varies like $1/R^{2.63}$ and the size of the satellite could not be much larger than $R = 300$ m to have a significant number of hits in 10^5 years, even if $F/\xi = 10$ (Fig. 4). On the other hand, if the meteoroids follow N_1 , then (16) holds, and the flux drops off more gently, like $1/R^{0.4}$; but the flux is already small for $R = 100$ m, regardless of F/ξ , and smaller still for satellites with $R > 300$ m (Fig.3).

6. Discussion

The upshot of these results is that the number of shape-changing hits needed to produce a long random walk depends sensitively on whether the meteoroid flux follows N_1 or N_2 , and what the value of F/ξ is. Most of the satellites listed at W. R. Johnston's website have $R < 300$ m, so that for them random walks may be possible. However, random walks for satellites with $R > \sim 300$ m are unlikely regardless of the flux or the value of F/ξ ; the meteoroid masses are too big to give much of a flux for these larger sized satellites.

It may be that a random walk is not necessary to lengthen the dynamical lifetime. A non-equilibrium shape for the satellite is required for BYORP to operate. Perhaps only one or a few hits are required to jostle a pile into something like an equilibrium shape (**Tanga *et al.*, 2009**). In other words, the arrow points the wrong way in Fig. 1. A perfectly equilibrium shape would shut down BYORP completely and the orbit would stop evolving via BYORP.

The whole argument here assumes that the satellites are rubble-piles. However, asteroids smaller than ~ 50 m are often solid objects, as deduced from their rapid rotation. Rotationally fission asteroids (e.g., **Jacobson and Scheeres, 2011**) may simply throw off a monolith, which becomes the satellite. Hence the results found above may apply mainly to small satellites, but not too small so that they are monoliths.

So, do shape-changing impacts significantly lengthen the dynamical lifetime of binary NEAs? Given the uncertainties in the assumed parameters, nothing conclusive can be derived from the above analysis. However, the results are tantalizing enough to warrant a closer look. Do the meteoroid masses really follow N_1 as given by (15), or N_2 as given by (16), or something in between, as suggested by the lunar data? What are reasonable values for F/ξ ? Granular models such as those of **Schwartz *et al.* (2012)**; **Tancredi *et al.* (2012)**, **Sanchez and Scheeres (2011)**, and **Richardson *et al.* (2009)** would be of great aid in settling what might be reasonable values of F/ξ .

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Figure captions

Figure 1

The spherical satellite (left) fissions into a contact binary (right) after colliding with a meteoroid. Neither the original object nor the objects in the contact binary have any rotation. The mass and volume of the original satellite are conserved, so that no mass is ejected. The dimensions in the figure are approximately correct for the smaller contact object having $f = 0.315$ times the radius of the original satellite.

Figure 2

The fractional change F in the gravitational potential energy U after the spherical satellite of radius R fissions into a contact binary, plotted as a function of f , where the smaller contact object has a radius fR . The mass and volume of the original satellite are conserved, so that no mass is ejected. The star indicates $f = 0.315$, the value for which $F = 0.01$.

Figure 3

H_1 , the number of hits in 10^5 years for meteoroids following N_1 , as a function of R . The open circles are for $(F/\xi) = 0.1$; the solid circles are for $(F/\xi) = 1.0$, while the open squares are for $(F/\xi) = 10$.

Figure 4

H_2 , the number of hits in 10^5 years for meteoroids following N_2 , as a function of R . The open circles are for $(F/\xi) = 0.1$; the solid circles are for $(F/\xi) = 1.0$, while the open squares are for $(F/\xi) = 10$.







